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VELOCITY OF DETONATION IN 'IDEAL' EXPLOSIVES WITH INERT ADDITIVES

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Velocity of Detonation in
'Ideal' Explosives with Inert Additives

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Velocity of Detonation in
'Ideal' Explosives with Inert Additives

Abstract

A simplified approximate method for estimating the 'ideal' detonation velocity of pure explosives is given. Theoretical applications of this method are included to study the effect upon velocity of initial temperature and of incomplete reaction of the explosive. A method for calculating the ideal velocity of a pure explosive with inert ingredients is also given. Several different mixtures are considered, and the calculated velocities are reported. Where experimental data are available, the calculated and observed results are compared.

Introduction

Solution of the thermo-hydrodynamic problem for an explosive by the "inverse" method is dependent upon an experimental 'ideal' detonation velocity vs. initial density relationship. (An 'ideal' detonating explosive is defined as one in which the velocity does not increase with increasing diameter of the charge.) Using this empirical relationship, the various thermodynamic variables for the detonation process can be calculated. Difficulty immediately arises, however, if such experimental data for a particular explosive are not available. No completely satisfactory method for predicting detonation velocities has yet been suggested. The first part of this report is an attempt to present a simplified method for predicting approximately the ideal velocities of pure explosives, hence, providing an approximate solution to the thermo-hydrodynamic problem. Due to the assumptions which are made in this method, only an estimate of the velocities can be expected. The method was applied, however, to some explosives with known velocities, and the results agreed favorably with the observed values.

An investigation was also made of the effect of solid diluents in pure explosives. The second part of this paper develops a method by

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which velocities may be predicted approximately for explosive-inert mixtures. This method was successfully applied in calculations of the detonation velocities for several mixtures, agreement with the observed values being usually within experimental error of measurement. This theory includes the compressibility of the inert substance. Hence, if measured velocities of a particular mixture were given, by an "inverse" solution the compressibility of the inert could be calculated.

Ideal Velocities in Pure Explosives

It was demonstrated in T. R. VI that any reasonable choice of the form of the equation of state may be used with satisfactory results in the solution of the thermo-hydrodynamic problem of an explosive. In this report the relation

$$pv = nRTe^x \quad (1)$$

or equivalently, the equation

$$pv = nRT + p\alpha \quad (2)$$

was used as the form of the equation of state. By eliminating between (1) and (2), the relation

$$\alpha = v(1 - e^{-x}) \quad (3)$$

is obtained. Equation (3) explicitly relates the two forms (1) and (2). Furthermore, it was concluded in T. R. VI that present methods of measuring thermo-hydrodynamic variables are insufficient to distinguish between reasonable forms of equations of state. The following is an attempt to consider the converse of this conclusion. That is, by "fixing" an equation of state, assumed valid for most explosives, it should be possible to make reasonable theoretical estimates for the values of the thermo-hydrodynamic quantities, including detonation velocity. Since the "inverse" method of solving the thermo-hydrodynamic problem requires only one empirical relationship, namely the velocity-density curve, it is necessary in the proposed method only to reduce the number of degrees of

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freedom of (1) or (2) by one, in order that the proposal be realized. The fundamental assumption made to satisfy this condition is that the variable x and equivalently α are known functions of v . That is, there exist 'universal' relationships $x = X(v_2)$ and $\alpha = A(v_2)$, valid for (most) explosives. This assumption is not justified explicitly, but the following comments are suggested in respect to the particular choice:

(1) There is a need for a simple, practical method of predicting velocities. The above fundamental assumption leads to such a method. The results, dependent on the validity of the assumption, can easily be checked with some known calculations or observed data.

(2) The fundamental assumption agrees with a previous observation of Cook⁽¹⁾; viz, that most explosives satisfy the same α vs. v_2 relationship. Figure 1 is a reprint of the results of his study.

(3) In T. R. VI two different sets of experimental velocity data were used in determining an equation of state for EDNA. If it were assumed that these two sets of data represented the extreme possibilities, then the effect of experimental error of velocity measurement on the equation of state would be that indicated in figure 2. Here a plot of x vs. v_2 is shown obtained from the results of the two sets of calculations given in tables IV and V of T. R. VI. It is clear that any choice of a functional relationship $x = X(v_2)$, which is within the limits given here, will predict the velocity of EDNA within the velocity limits of the two sets of results. It is also to be noted that there exists a liberal choice for such a function for this particular explosive. And under the assumptions stated, it is possible to accept the results of calculations obtained by use of any such function. Thus, it is reasonable to assume from these results that the choice of a universal relationship $x = X(v_2)$ will not be too critical if one is satisfied to compute velocities which are accurate only to within about ± 150 m/sec.

(4) After a specific choice, satisfying the fundamental assumption, has been made, the selection may or may not be satisfactory. If the latter is the case, then one can assume that an incorrect selection has

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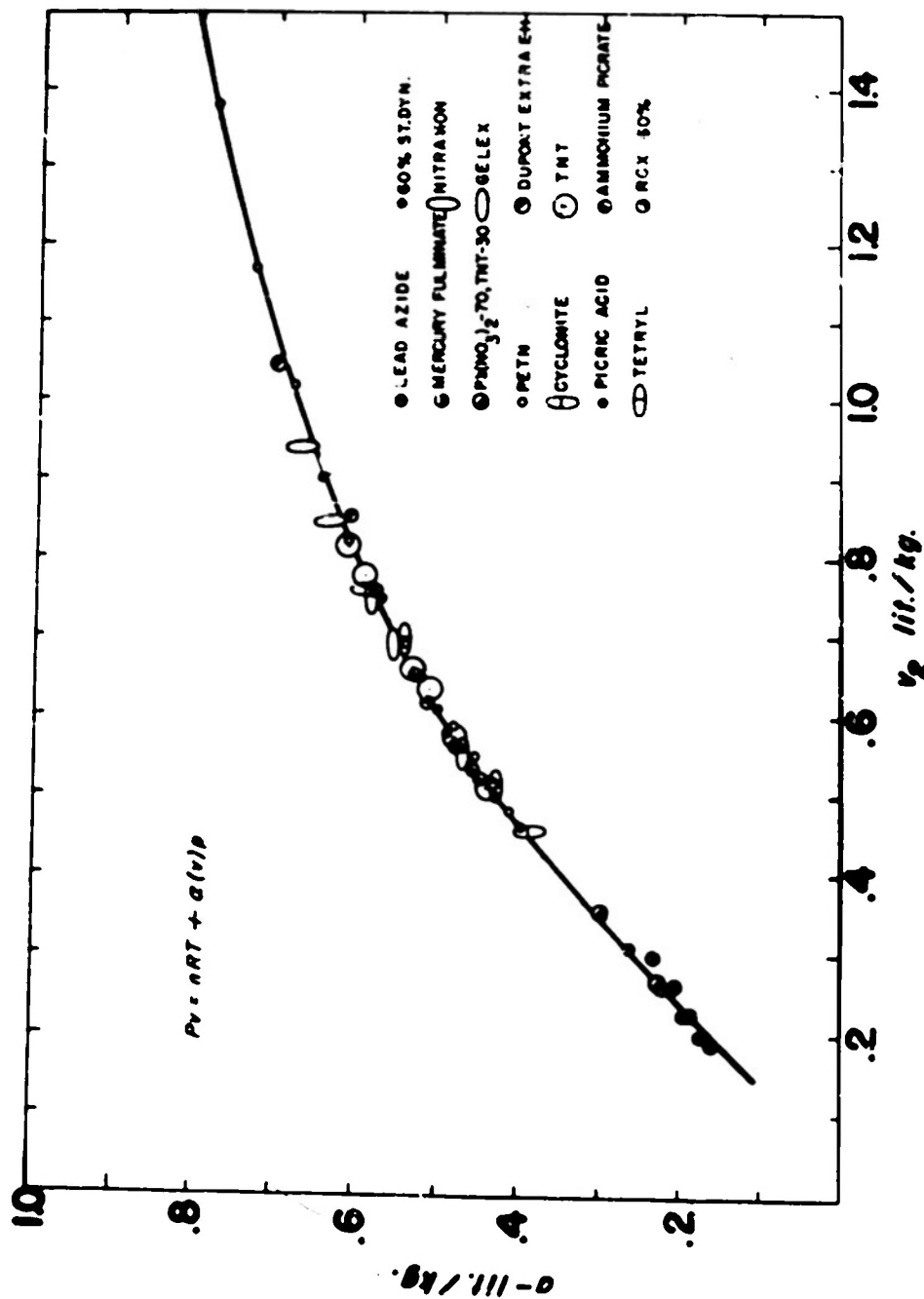


FIG.1 FROM THEORY OF DETONATION - M.A. COOK

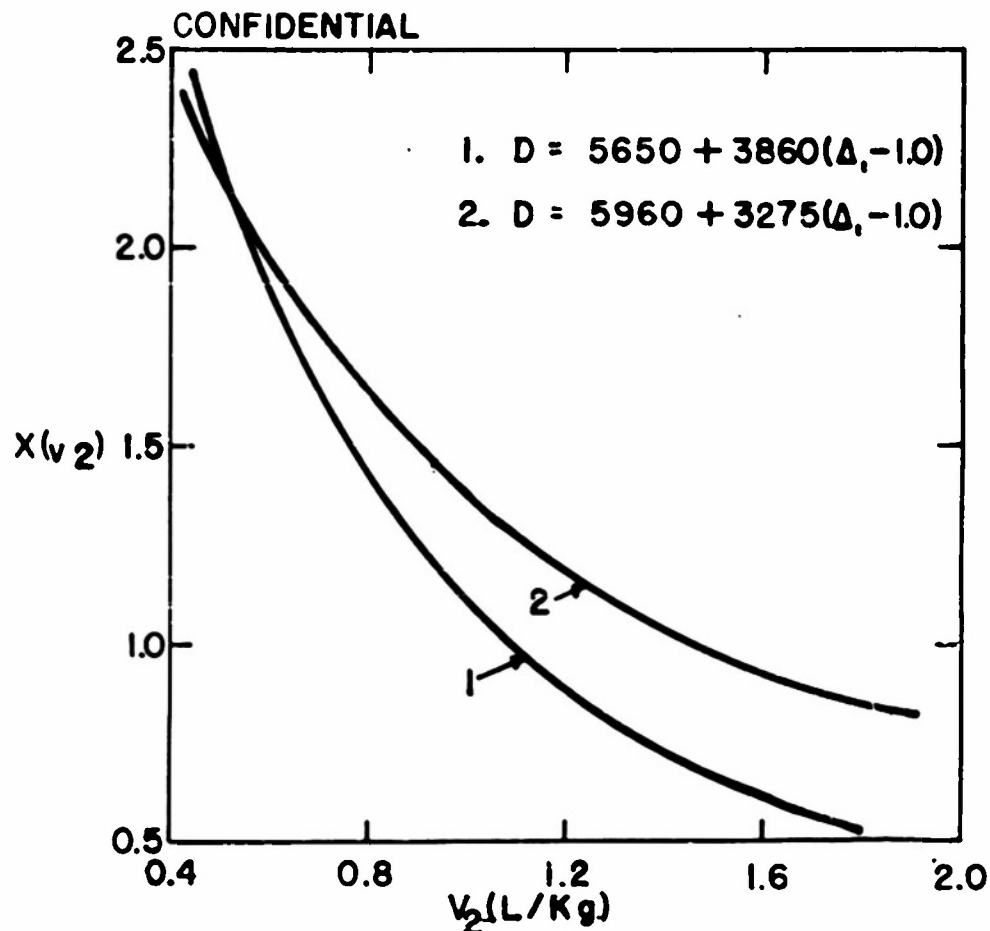


FIG. 2 COMPARISON OF EQUATIONS OF STATE FOR EDNA

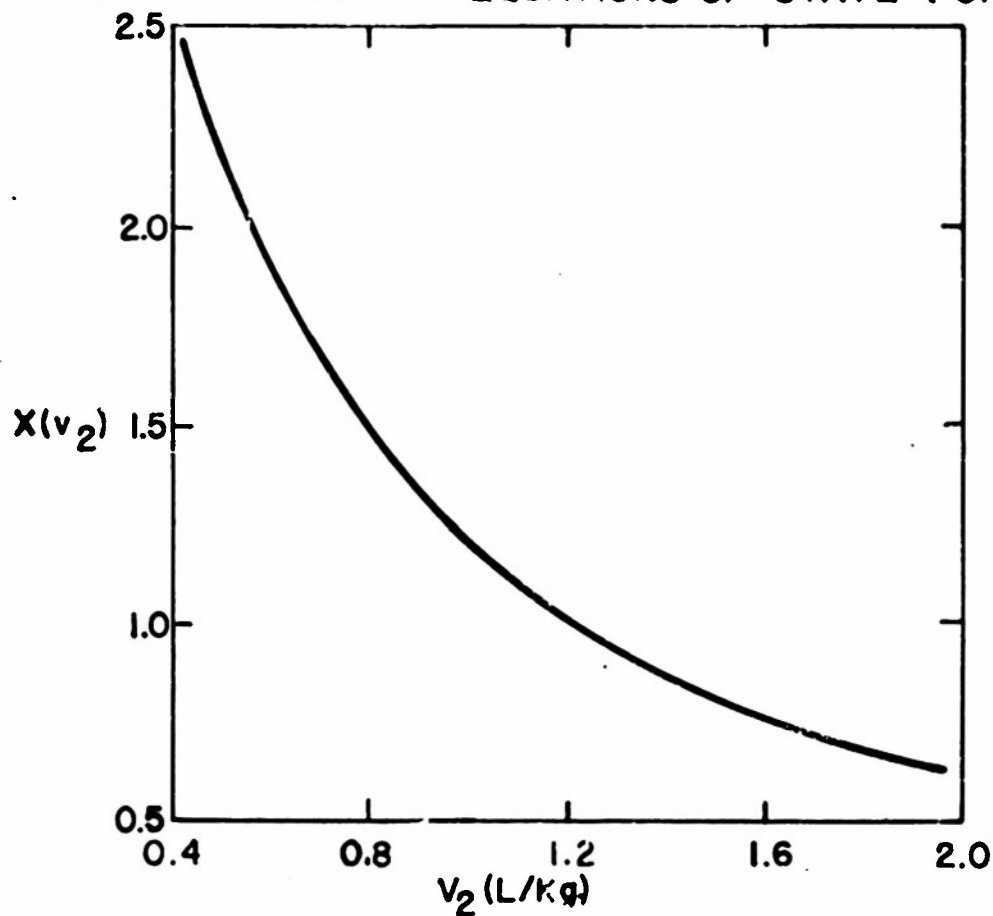


FIG. 3 ASSUMED $X=X(v_2)$ RELATIONSHIP
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been made, and for practical purposes attempt to correct or try to classify the explosives such that certain relationships will be valid for particular classes. Such work will depend upon further experimental investigations and theoretical calculations.

If the scheme is successful, it provides a simple method for determining velocities. The reasons for accepting the above fundamental assumption can then be sought with profit.

For an actual selection of a functional relationship $x = X(v_2)$, for this report all of the available evidence at hand was used. It was selected as a near approximation to the data of T. R. VI, VIII, and "Theory of Detonation".⁽¹⁾ The plot is given in figure 3, and a set of corresponding values is given in table I.

Two methods of solving the thermo-hydrodynamic problem will now be described. The first introduces the fundamental assumption which has just been discussed. The second considers further assumptions, which permits a simpler solution. The first requires a calculation of the products of detonation over the complete range of temperature and fugacity factors of interest for a particular explosive compound. The method given in the first part of T. R. VIII is available for this calculation. With this known composition, the total number of n of moles/kg of products of detonation, the chemical energy Q released in detonation, and the actual C_v and average \bar{C}_v heat capacities can be calculated for each temperature and fugacity factor considered. This method of computation is given in appendix II of T. R. V.

The method of solution of the thermo-hydrodynamic problem is similar to the method given in the second part of T. R. VIII. The difference is in the substitution of the assumed $x = X(v_2)$ relationship in place of the empirical velocity vs. density relationship. In order to facilitate this procedure, the following expressions have been computed on the basis of the particular selection of the $x = X(v_2)$ mentioned above.

$$\theta_0 = 1 + x - \left(\frac{dK}{dv_2} \right)_s \quad (4)$$

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Table I

Corresponding Relationships of
 x , v_2 , and $\log \widetilde{F}$ Under the Assumption of $x = X(v_2)$

x	v_2	$\log v_2$	$\log_{10} \widetilde{F}$	θ_0	$\log_{10} \widetilde{F} - NY_1$
0.6	2.050	0.312	0.35	1.59	0.36
0.7	1.736	0.240	0.57	1.68	0.58
0.8	1.514	0.180	0.78	1.77	0.79
0.9	1.343	0.128	1.01	1.86	1.02
1.0	1.202	0.080	1.24	1.95	1.26
1.1	1.085	0.035	1.48	2.05	1.50
1.2	0.992	9.996-	1.74	2.15	1.77
1.3	0.913	9.965-	2.02	2.24	2.05
1.4	0.845	9.927-	2.31	2.32	2.34
1.5	0.785	9.895-	2.62	2.39	2.66
1.6	0.732	9.864-	2.96	2.45	3.01
1.7	0.684	9.835-	3.33	2.53	3.39
1.8	0.643	9.808-	3.72	2.61	3.77
1.9	0.604	9.781-	4.15	2.62	4.25
2.0	0.568	9.754-	4.62	2.62	4.74
2.1	0.534	9.727-	5.13	2.55	5.30
2.2	0.499	9.698-	5.68	2.51	5.91
2.3	0.467	9.669-	6.29	2.50	6.61
2.4	0.437	9.640-	6.95	2.50	7.46

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$$\log_{10} \widetilde{F} = N(x + J - Y) - \log v_2 \quad (5)$$

$$NY_1 = N \int_{K(\infty)}^{K(v)} (e^x - 1) \frac{dK}{K} \quad (6)$$

where

$$N = \log_{10} e = 0.4343$$

and Y_1 is part of the integral Y appearing in T. R. VI and VIII. The values of these expressions corresponding to x 's in the range 0.6, 0.7, ..., 2.4 are given in table I.

To calculate the thermo-hydrodynamic quantities for various conditions, the equations of T. R. VIII are used, and the following method is suggested. Corresponding to a set of x values over a suitable range, say 0.6, 0.8, ..., 2.4, values for T and n are selected. Since the method of solution is one of successive approximations, the choice of values should be made to correspond to that which is expected. The integral

$$NY_2 = N \int_{n(\infty)}^{n(v)} (e^x - 1) \frac{dn}{n} \quad (7)$$

is computed, and from equation (2.13) of T. R. VIII,

$$\log_{10} F = (\log_{10} \widetilde{F} - NY_1) + NY_2 \quad (8)$$

Corresponding to the sets of T and $\log_{10} F$, the quantities n , Q , C_v , and \bar{C}_v are obtained. The temperature is then calculated by

$$T_2 = \frac{Q + T_1 \bar{C}_v}{\bar{C}_v - \frac{n R e^x}{2\theta}} \quad (9)$$

where

$$\theta = \theta_0 + \frac{n R e^x}{C_v} - \frac{v}{n} \left(\frac{dn}{dv} \right) s \quad (10)$$

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$R = 1.987 \cdot 10^{-3}$ for T in degrees Kelvin, and T_1 is usually taken to be 300°K .

If the calculated and assumed values of T and n agree, then these values are taken as part of the solution. In general, however, a few iterations will be required to satisfy these conditions. It is suggested that in proceeding from one iteration to the next the calculated values of n be used from the previous computation, but that the assumed and calculated values of T be averaged. This method was found to be successful in obtaining rapid convergence. Also, for computing the integral (7) and the derivative in (10), the approximation methods given in T. R. VIII are satisfactory.

The detonation velocity D and initial density Δ_1 are calculated by use of the formulae

$$D^2 = nRT_2 e^x (1 + \theta)^2 / \theta \quad (11)$$

$$\Delta_1 = \frac{\theta}{V_2(1 + \theta)} \quad (12)$$

where $R = 8.314$ for velocity in meters/sec. From these values one may provide a plot of the predicted velocity against initial density. The other thermodynamic quantities can be calculated by use of the equations in T. R. VI or VIII.

As an illustration of this method, the velocity of TNT was calculated. The results, designated by "Method B", are compared with those previously obtained in T. R. VIII, "Method A". Table II gives a tabulation of the thermo-hydrodynamic variables, and figure 4 gives a plot of the velocity-density relationship. It is clear that the results of Method A and B would be identical, providing the $x = X(v_2)$ relationship had been selected as that calculated by Method A. The difference in the two sets of values is thus the measure of the error for TNT, introduced by the fundamental assumption. The difference is insignificant for most of the quantities.

If the integrals in the log F function and derivatives in the θ function were neglected in the thermo-hydrodynamic calculations, it would

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Table II
Comparison of Calculated Thermo-hydrodynamic Quantities for TNT

	Method A			Method B			Method C		
x	1.00	1.60	2.20	1.00	1.60	2.20	---	1.60	2.20
Δ_1	0.53	0.95	1.47	0.58	0.99	1.50	---	1.04	1.56
v_2	1.33	0.76	0.52	1.20	0.73	0.50	---	0.73	0.50
n	38.9	31.8	24.2	38.7	31.6	24.0	---	30.1	23.4
Q	680	870	1125	685	883	1135	---	945	1175
\bar{C}_v	.304	.334	.375	.305	.335	.376	---	.340	.379
$W \cdot 10^{-3}$	1.04	1.34	1.48	1.07	1.34	1.52	---	1.19	1.45
$p_2 \cdot 10^{-4}$	1.93	6.13	14.1	2.17	6.40	14.6	---	6.10	14.0
$D \cdot 10^{-3}$	3.50	4.85	6.48	3.52	4.83	6.31	---	4.95	6.38
$T \cdot 10^{-3}$	2.93	3.58	4.05	2.97	3.59	4.08	---	3.58	4.02
log F	1.13	2.69	4.85	1.21	2.72	4.98	---	2.96	5.68

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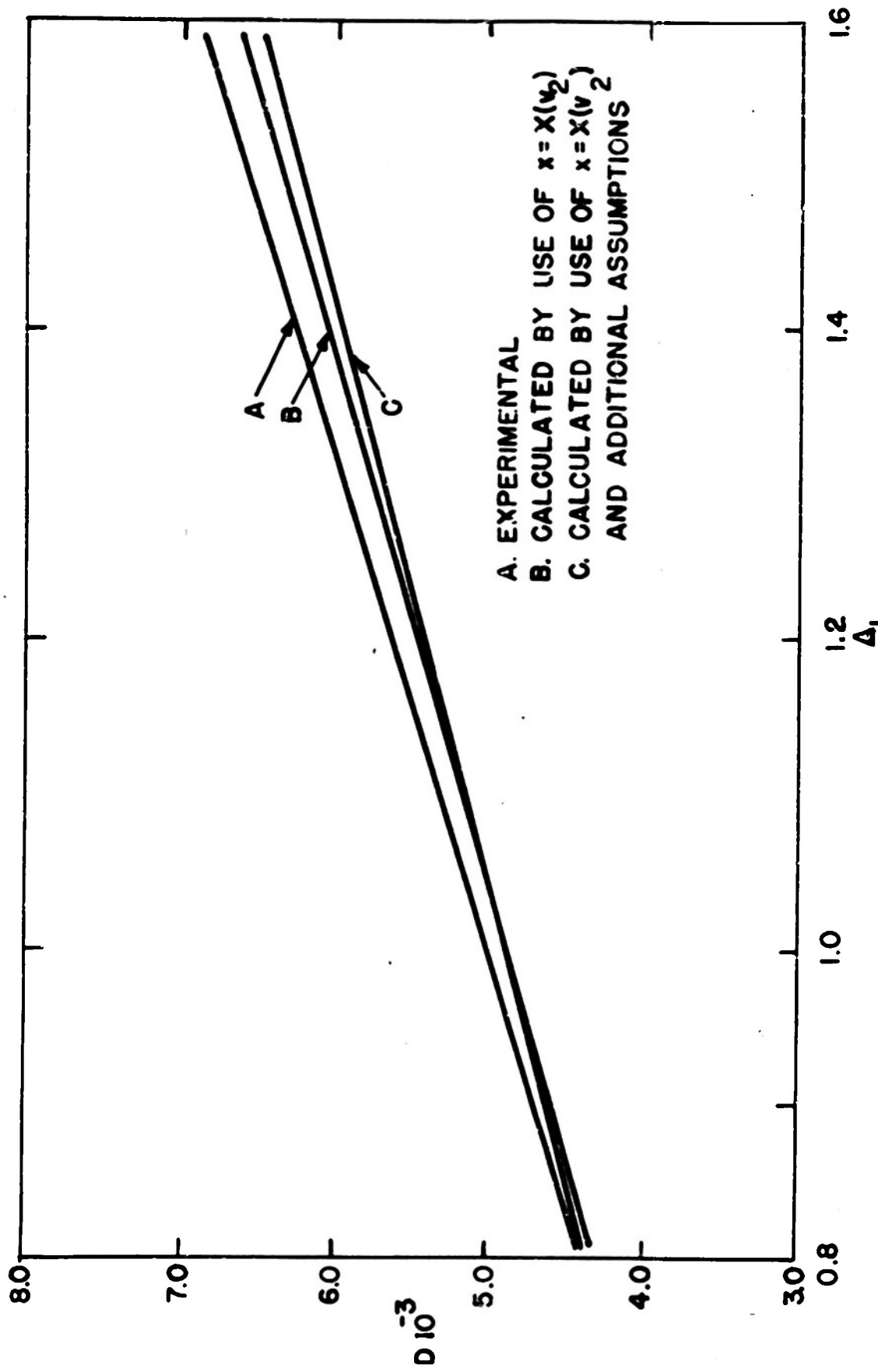


FIG.4 VELOCITY-DENSITY RELATIONSHIP FOR TNT BY COMPARATIVE METHODS

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be possible to devise a very simple procedure for predicting detonation velocities. Under these conditions it is unnecessary to compute a complete table of composition against temperature and fugacity factors, but sufficient to calculate the particular composition at the conditions of interest. Assuming in accordance with experience that the velocity-density relationship is linear, solutions of the thermo-hydrodynamic problem at two specific set of conditions will be sufficient to determine this relationship.

The following method was found satisfactory in solving the problem under these strong assumptions. For a given x , obtain from table I a corresponding value of $\log F$. Since in general Y_1 and Y_2 tend to cancel each other, $\log F$ is a better approximation for the fugacity factor than $\log F - NY_1$. Using this value $\log F$, and assuming a temperature T_2 , the corresponding composition and n , Q , C_v , and \bar{C}_v are calculated. Substituting these values into equations (9) and (10), where the derivative in (10) is neglected, a value for T_2 is calculated. Iterating as previously suggested, a consistent solution is obtained when the assumed and calculated values of T_2 agree. The velocity-density relationship is then obtained by use of equations (11) and (12). Two such solutions determine the desired linear relationship.

As an illustration of this method, the case of TNT is considered once again. The results are given in table II under Method C, and in figure 4, curve C. Once again, the method gives results which agree approximately with the complete and accurate solution. Additional calculations verified that this method gives a linear velocity-density relation. Hence, this is valid assumption for this scheme. Furthermore, the difference between curves A and B in figure 4 indicates the significance of a correct functional relation $x = X(v_2)$. The difference between curves B and C indicate the error introduced by the additional assumptions discussed here. Appreciating the magnitude of some of the terms neglected by this method, one can only explain the reasonable results on the basis

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of compensating errors. Incidentally, for computing relative velocities instead of absolute ones, the approximation Method C is actually quite good.

As applications of this method, two problems were considered for the case of TNT. First, the effect of initial temperature on detonation velocity, and second, the effect of non-reaction in an explosive. Since the calculations are made by this approximation method, these effects are to be studied qualitatively. Corrections could be made, however, by extrapolation and use of the correct velocity-density relation.

The first problem is answered by simply varying the parameter T_1 (usually taken to be 300°K) in equation (9). The set of temperature values 200, 300, 400, and 500°K were considered for the case of TNT, and the velocity-density curve was calculated for each such value. The results are given in table III. The effect of this parameter is also demonstrated in figure 5, where the velocity density curves are plotted. It is to be observed that the effect is not appreciable on any of the thermo-hydrodynamic quantities, but that an increase of initial temperature would tend to increase the detonation velocity.

The second problem is solved by considering that a specific weight percentage of explosive reacts. That is, if M_1, \dots, M_m is the initial composition (in gram/atom/100gram) of the m elements present in the composition, then $N_w M_1, \dots, N_w M_m$ is the composition of an explosive equivalent to an N_w reaction of the first explosive. Calculations were carried out for TNT at two different densities, taking the set 0.80, 0.60, and 0.40 as the values for N_w . These results are given in table IVA, and the velocity-density curves are given in figure 6. The effect of non-reaction is clearly demonstrated by these results.

In T. R. IV the simple approximation equation

$$\frac{D}{D^*} = \left(\frac{n}{n^*} \right)^{1/2} = (N_w)^{1/2} \quad (13)$$

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Table III

Effect of Initial Temperature on Relative Velocity for TNT

T_1	x	n	Q	\bar{C}_v	$T \cdot 10^{-3}$	Δ_1	$D(T_1)/D(300^\circ K)$
200	1.6	29.9	965	0.340	3.53	1.04	0.992
300	1.6	30.1	945	0.340	3.58	1.04	1.000
400	1.6	30.2	930	0.341	3.64	1.04	1.011
500	1.6	30.4	920	0.341	3.71	1.04	1.022
200	2.2	23.4	1185	0.379	3.93	1.56	0.989
300	2.2	23.4	1175	0.379	4.02	1.56	1.000
400	2.2	23.5	1130	0.380	4.12	1.56	1.013
500	2.2	23.5	1165	0.382	4.23	1.56	1.027

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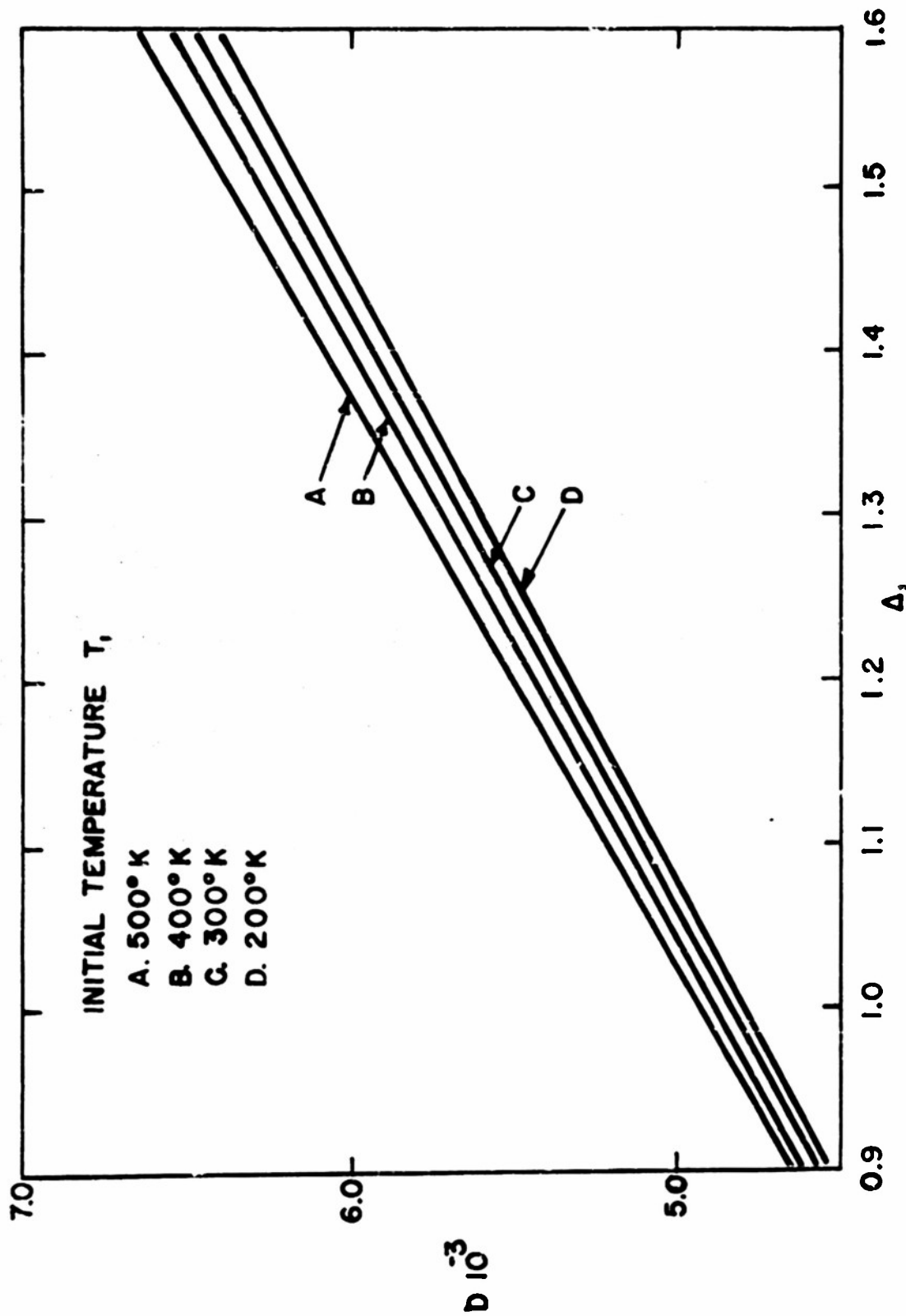


FIG.5 INITIAL TEMPERATURE EFFECT ON VELOCITY-DENSITY FOR TNT

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Table IV A

Effect of Partial Reaction on Relative Velocity of TNT

N_w	n	Q	\bar{C}_v	$T \cdot 10^{-3}$	Δ_1	D/D^*
1.00	30.1	945	.340	3.58	1.04	1.00
0.80	24.2	755	.284	3.46	1.04	0.88
0.60	18.2	544	.204	3.42	1.04	0.76
0.40	12.1	350	.132	3.40	1.04	0.62
1.00	23.4	1175	.379	4.02	1.56	1.00
0.80	18.7	927	.304	3.99	1.56	0.89
0.60	13.9	675	.227	3.95	1.56	0.76
0.40	9.1	417	.143	3.93	1.56	0.61

Table IV B

Comparison of $N_w^{1/2}$, $(n/n^*)^{1/2}$, and D/D^* for TNT

N_w	$\Delta_1 = 1.04$			$\Delta_1 = 1.56$	
	$N_w^{1/2}$	$(n/n^*)^{1/2}$	D/D^*	$(n/n^*)^{1/2}$	D/D^*
0.80	0.894	0.897	0.883	0.894	0.889
0.60	0.775	0.777	0.760	0.771	0.762
0.40	0.632	0.634	0.624	0.624	0.613

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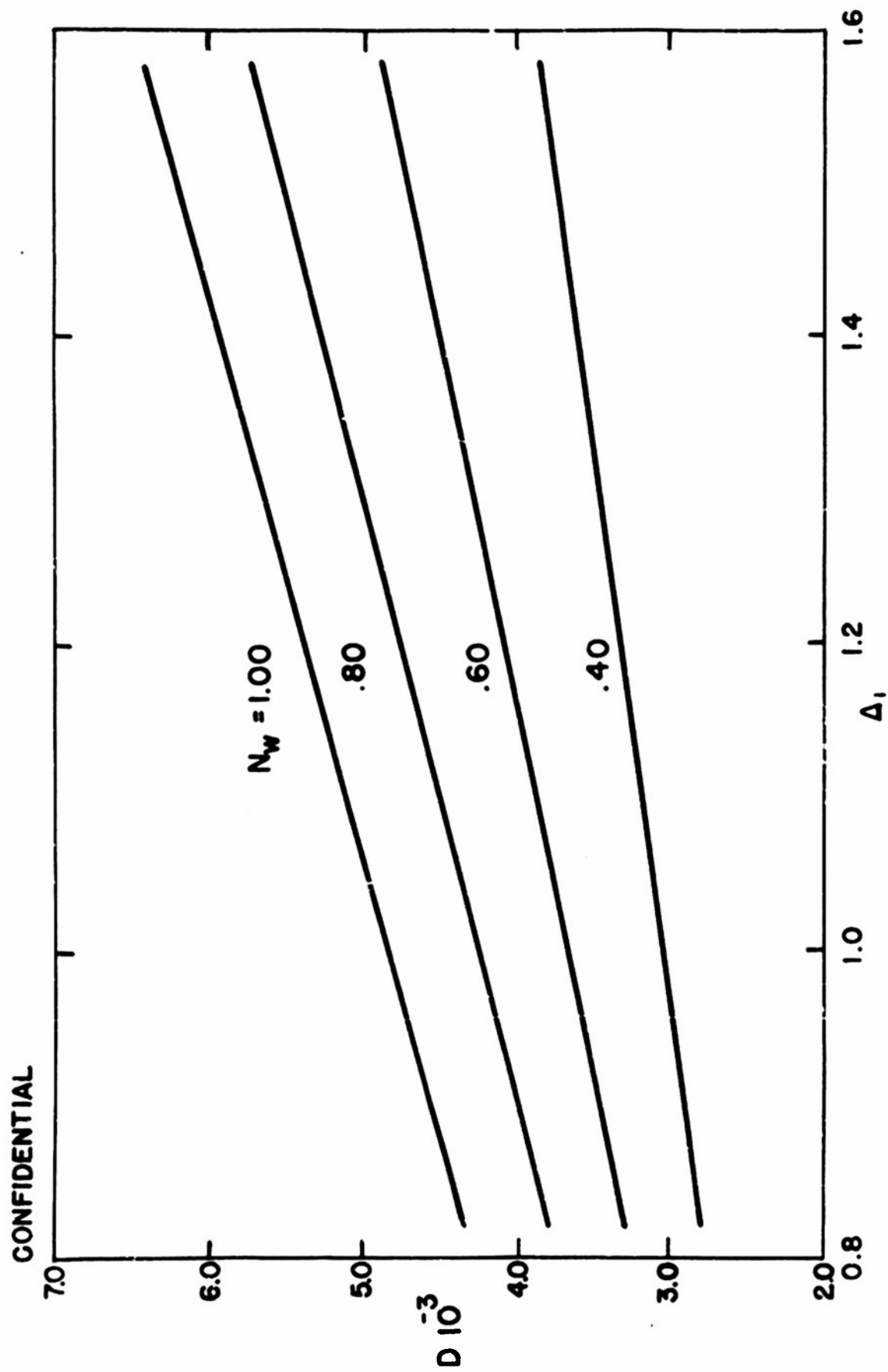


FIG.6 EFFECT OF NON-REACTION ON VELOCITY-DENSITY FOR TNT

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was derived, where D and n are, respectively, the detonation velocity and the total number of moles/kg of explosives products for the incompletely reacting explosive, and D^* and n^* are the corresponding quantities for complete reaction under 'ideal' conditions. Table IVB gives a tabulation of the three terms of (13) for TNT at the two densities and set of values of N_w reported in table IVA. Since ratios only are here considered, the results are quantitative, and agree with the prediction of equation (13).

Detonation Velocity in Explosives with Solid Inert Additives

As is clear from the study of the preceding section, air is an effective diluent for explosives. The velocity-density relationship is practically linear, with velocity decreasing as the volume fraction of air is increased. It is of interest to study the effect of other diluents in pure explosives. The following discussion is concerned with the effect of adding solid, non-explosive materials to an explosive.

Let M and Δ_1 be the mass and density, respectively, of the explosive-inert mixture, and M_i and Δ_i the corresponding quantities of the component i , (pure explosive or solid inerts). The crystal density Δ_c of the mixture is

$$\Delta_c = (\sum_i M_i) (\sum_i \frac{M_i}{\Delta_i})^{-1} = \Delta_1 (1 - A)^{-1} \quad (14)$$

where i runs over the indices of the solid components, and A is the volume fraction of air in the mixture. That is,

$$\Delta_1 = \Delta_c (1 - A) \quad (15)$$

In the following, the same volume fraction of air will be assumed in the mixtures as in the case of the ideal pure explosive. That is

$$\frac{\Delta_1}{\Delta_1^*} = \frac{\Delta_c}{\Delta_c^*} \quad (16)$$

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where Δ_1^* is the crystal density of the pure explosive. Here only one solid diluent is considered. Hence, under these conditions, if N_w is the weight fraction of explosive, $1 - N_w$ is the weight fraction of the inert, and

$$\Delta_c = \left(\frac{N_w}{\Delta_E} + \frac{1 - N_w}{\Delta_I} \right)^{-1} \quad (17)$$

where Δ_E and Δ_I are the crystal densities of the explosive and inert, respectively.

In addition to these preliminary considerations, the following were applied in calculation of the detonation velocity of an explosive-inert mixture. Using the covolume equation of state (equation (2)) the ideal detonation velocity D^* is given by

$$D^* = \frac{v_1^*}{v_1^* - \alpha^*} \frac{\beta^* + 1}{(\beta^*)^{1/2}} (n^* R T_2^*)^{1/2} \quad (18)$$

where

$$\beta^* = \frac{C_v^* + n^* R}{C_v^*} - \left(\frac{d\alpha}{dv} \right)_s^* \quad (19)$$

Here the relationships (18) and (19) refer to the case of a pure ideal explosive, and corresponding non-starred equations describe the ideal conditions of an explosive-solid inert mixture.

For all practical purposes if the explosives are compared at the same relative free space, $\beta = \beta^*$. Furthermore, the term $(\beta^* + 1)/(\beta^*)^{1/2}$ is quite insensitive to β^* for the usual range of values of this quantity. For example, a 20 per cent increase in the value of β^* near $\beta^* = 0.5$ corresponds to less than 3 per cent decrease in the value of $(\beta^* + 1)/(\beta^*)^{1/2}$. Hence, by dividing the unstarred relationship corresponding to (18) by the equation (18),

$$\frac{D}{D^*} = \frac{a}{a^*} \left(\frac{n T_2}{n^* T_2^*} \right)^{1/2} \quad (20)$$

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where

$$a = (1 - \Delta_1 \alpha)^{-1}, \quad a^* = (1 - \Delta_1^* \alpha^*)^{-1} \quad (21)$$

The situation of an explosive-inert mixture is similar to the problem of non-reaction in a pure explosive. Here, unreacted explosive is to be considered as inert. Under these conditions, as is indicated on page 20 of T. R. VI, $T_2 = T_2^*$. This is demonstrated also by the results reported in table IVA for the case of TNT. At $\Delta_1 = 1.56$, the error is less than 2.5 per cent in assuming the complete reaction temperature for the case of 40 per cent reaction in pure TNT. Furthermore, assuming complete reaction of the pure explosive, $n/n^* = N_w$. Therefore, from (20),

$$\frac{D}{D^*} = \frac{a}{a^*} (N_w)^{1/2} \quad (22)$$

If the solid inert is considered to be non-reacting explosive, then it is clear by (21) that equation (22) would reduce to (13). For under these conditions, the initial density and co-volume of the "mixture" is the same as the pure explosive.

Assuming that D^* and a^* are known for a particular ideal explosive, D can be calculated for a specific N_w in terms of a . Also, by (21), a is a simple function of the density Δ_1 and co-volume α of the mixture. Since Δ_1 is readily obtainable, the only problem is in obtaining α .

To calculate the co-volume of the mixture, the following is considered. First,

$$\alpha = \alpha_E + \alpha_I \quad (23)$$

where α_E is the part of the total co-volume contributed by the explosive, and α_I that of the inert. It is assumed that $\alpha_E = N_w \alpha^*(p)$ where $\alpha^*(p)$ is the co-volume of the ideal pure explosive, corresponding to the pressure p of the mixture explosive. Furthermore, $\alpha_I = (1 - N_w) v_I(p)$, where $v_I(p)$ is the specific volume of the inert at pressure p .

The parameter $\alpha^*(p)$ is obtained from the solution of the thermo-hydrodynamic problem of the pure explosive. It is simply the value of α^*

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corresponding to the pressure p . If the complete co-volume-pressure relationship has not been calculated for a particular explosive, the following approximation is satisfactory. From hydrodynamic theory

$$p = \Delta_1 DW \quad (24)$$

and

$$\frac{D}{W} = \frac{v_1}{v_1 - v_2} \quad (25)$$

If it is assumed now that $v_2 = cv_1$, where c is constant, then

$$p = \Delta_1 (1 - c)D^2 \quad (26)$$

If v_2 is known for a particular Δ_1 , then $c = v_2/\Delta_1$. This assumption is a valid assumption for most solid explosives, and corresponding values of v_2 and Δ_1 are obtainable for various important explosives in "Theory of Detonation"⁽¹⁾.

As part of the procedure for calculating the velocities of the explosive-inert mixtures, it is advisable that a plot be made of $\alpha^*(p)$ vs. p/p^* , where p^* is the pressure of the pure explosive, corresponding to a density Δ_1^* . Such a plot is given in figure 7 for TNT at two different densities. Similar curves, which parallel these, are easily obtainable for other explosives.

The calculation of $v_I(p)$ depends upon the following properties of solids. It is convenient to use the identity

$$v_I(p) \equiv \frac{1}{\Delta_I} \frac{v_I(p)}{v_I} \quad (27)$$

where v_I is the specific volume of the inert at one atmosphere pressure, and Δ_I is the initial density of the inert. Introducing the compressibility factor $\beta_0(p)$ of the inert at pressure p ,

$$\frac{v_I(p)}{v_I} = 1 - \beta_0(p)p$$

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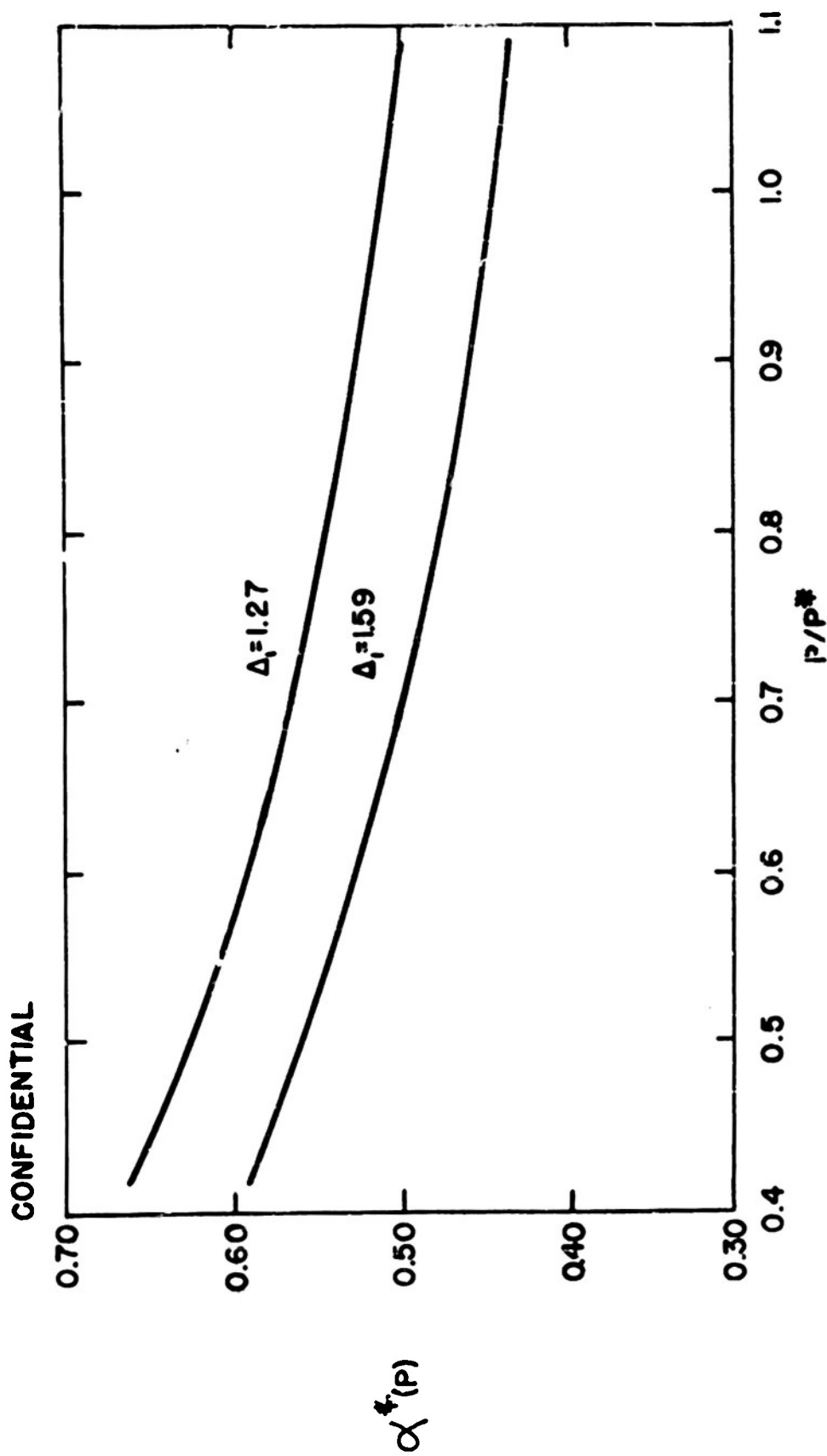


FIG.7 COVOLUME-PRESSURE RELATIONSHIP FOR TNT

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Also in "Properties of Solids"⁽²⁾, Cook has derived the following relationship between the compressibility at atmospheric pressure and that at pressure p

$$\beta_o(p) = \beta_o \frac{1 - \beta_o p + (\beta_o p)^2}{(1 + 2/3 \beta_o p)(1 + 1/3 \beta_o p)} \quad (29)$$

where β_o is the compressibility of the solid inert at one atmosphere. Also since

$$p^* = \Delta_1^* D^* \left(\frac{nRT_2}{\beta} \right)^{1/2} \quad (30)$$

under the previous assumptions,

$$\frac{p}{p^*} = \frac{\Delta_1}{\Delta_1^*} \frac{D}{D^*} (N_w)^{1/2} \quad (31)$$

The procedure in calculating D for specific values of N_w , Δ_1 and β_o , and known D^* , p^* , and Δ_1^* , is as follows. Assuming a value of the ratio D/D^* , the ratio p/p^* is computed by means of equation (31). The value of $\beta_o p$ is then obtained, and by (29) the value of $\beta_o(p)p$, hence, by (28) the value of $v_I(p)/v_I$. The value of the co-volume α is immediately obtained, using the density of the inert, the $\alpha^*(p)$ vs. p/p^* relationship, and equation (23). Hence, by (21) and (20), a calculated value of D/D^* is obtained. If this computed value agrees with the assumed ratio, the solution is complete. If it does not agree, then the process is repeated, using the average value of the assumed and calculated values of D/D^* . This iteration procedure usually converges very rapidly.

NOL⁽³⁾ reported a set of experimental data for TNT, mixed respectively with NaCl, $Ba(NO_3)_2$, $PbSO_4$, and Cu. A value of $D^* = 6670$ meters/sec. was reported here for a density $\Delta_1 = 1.59$. This 'ideal' velocity value was used in this study, even though it is low, since the calculated and observed velocities are compared directly. Also, for this study the experimental velocities are corrected for the same relative air space in the mixtures as in the pure TNT measurements. The results of this calculation are

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shown in table V. Figure 8 is included in the case of TNT - Cu comparing graphically the experimental and calculated results.

Further calculations were made for TNT - NaCl, TNT - Al, TNT - NaNO_3 , 50-50 Pentolite - NaCl, RDX - NaCl, and Comp B - Al, assuming conditions for no reaction of the Al and NaNO_3 . These results are given in table VI. The velocity data for the pure explosives listed here were taken from measurements of NDRC at Bruceton⁽⁴⁾. References (1) and (5) were used to obtain the compressibilities of the inert substances. The α^* vs. p relation for TNT is given in figure 7; the same relation for the other three explosives was obtained by the above mentioned approximation method, using values for c calculated from the data given in "Theory of Detonation"⁽¹⁾. Figures 9 and 10 are included to indicate the effect of dilution on detonation velocity over a range of densities.

Experimental work is now in progress on this project to obtain velocities for some of the mixtures considered above. Wherever available, these results are reported in table VI. A comparison of the calculated and experimental values reveals a satisfactory agreement.

It is to be noted that if a measured velocity of a particular mixture is given, then by an 'inverse' method of solution, the compressibility of the inert can be calculated. This would permit one to 'measure' compressibility of solids at pressures considerably beyond those reported by Bridgman.

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Table V: Comparison of Calculated and Observed⁽³⁾
Velocities for TNT-Inert Mixtures

TNT: $D^* = 6670^*$, $\Delta_1^* = 1.59$

Inert	M_w	Δ_1	Calculated $D \cdot 10^{-3}$	Observed [*] $D \cdot 10^{-3}$
NaCl	0.90	1.61	6.52	6.54
	0.65	1.71	6.11	6.20
	0.50	1.78	5.85	5.67
Ba(NO ₃) ₂	0.90	1.65	6.41	6.53
	0.50	2.08	5.30	5.48
	0.30	2.39	4.71	4.66
	0.27	2.44	4.62	4.60
Cu	0.90	1.73	6.47	6.63
	0.80	1.90	6.22	6.31
	0.70	2.10	5.94	6.12
	0.60	2.36	5.66	5.56
	0.50	2.68	5.37	5.26
	0.40	3.12	5.07	5.25
	0.30	3.70	4.76	4.86
	0.27	3.92	4.67	4.70
PbSO ₄	0.90	1.72	6.45	6.53
	0.80	1.86	6.21	6.35
	0.70	2.04	5.96	6.15
	0.50	2.52	5.42	5.60
	0.30	3.27	4.79	4.87
	0.27	3.42	4.68	4.89

* NavOrd Report 1538. Velocities corrected to same air space as pure TNT measurements. $D^* = 6670$ is low for the ideal velocity at this density. It was used uncorrected since only the ratio of D/D^* is of interest.

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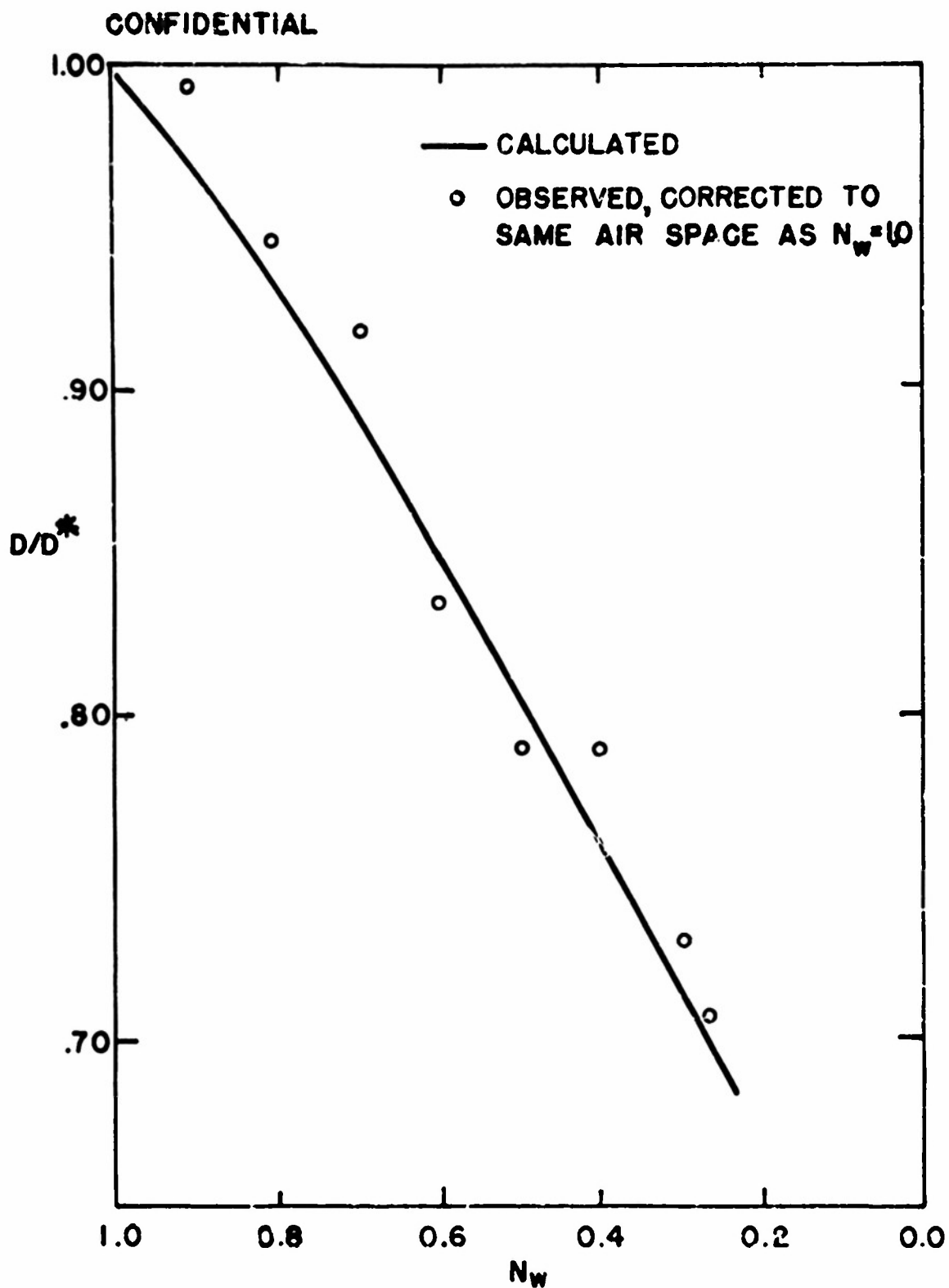


FIG.8 EFFECT OF DILUTION OF TNT WITH COPPER

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Table VI: Velocity Predictions and some Observations

Mixture	Δ_1^*	$D^* \cdot 10^{-3}$	N_w	Δ_1	$D \cdot 10^{-3}$ (Calc.)	$D \cdot 10^{-3}$ (Obs.)
TNT-NaCl	1.59	6.91	0.90	1.63	6.77	6.75
	1.59	6.91	0.70	1.71	6.49	6.51
	1.59	6.91	0.60	1.76	6.94	6.27
TNT-Al*	1.56	6.81	0.80	1.69	6.52	
TNT-NaNO ₃ *	1.59	6.91	0.50	1.84	6.18	
RDX-NaCl	1.26	6.86	0.70	1.32	5.96	5.80
	1.36	7.20	0.40	1.51	4.72	5.00
Pentolite-NaCl	1.60	7.34	0.70	1.83	6.94	6.93
	1.20	6.10	0.70	1.28	5.31	
Comp B-Al*	1.65	7.64	0.80	1.78	7.55	

* Assuming no reaction in the detonation head. This should apply approximately for 65 + mesh Al and 20-30 mesh NaNO₃ for charges in 5 cm. diameter.

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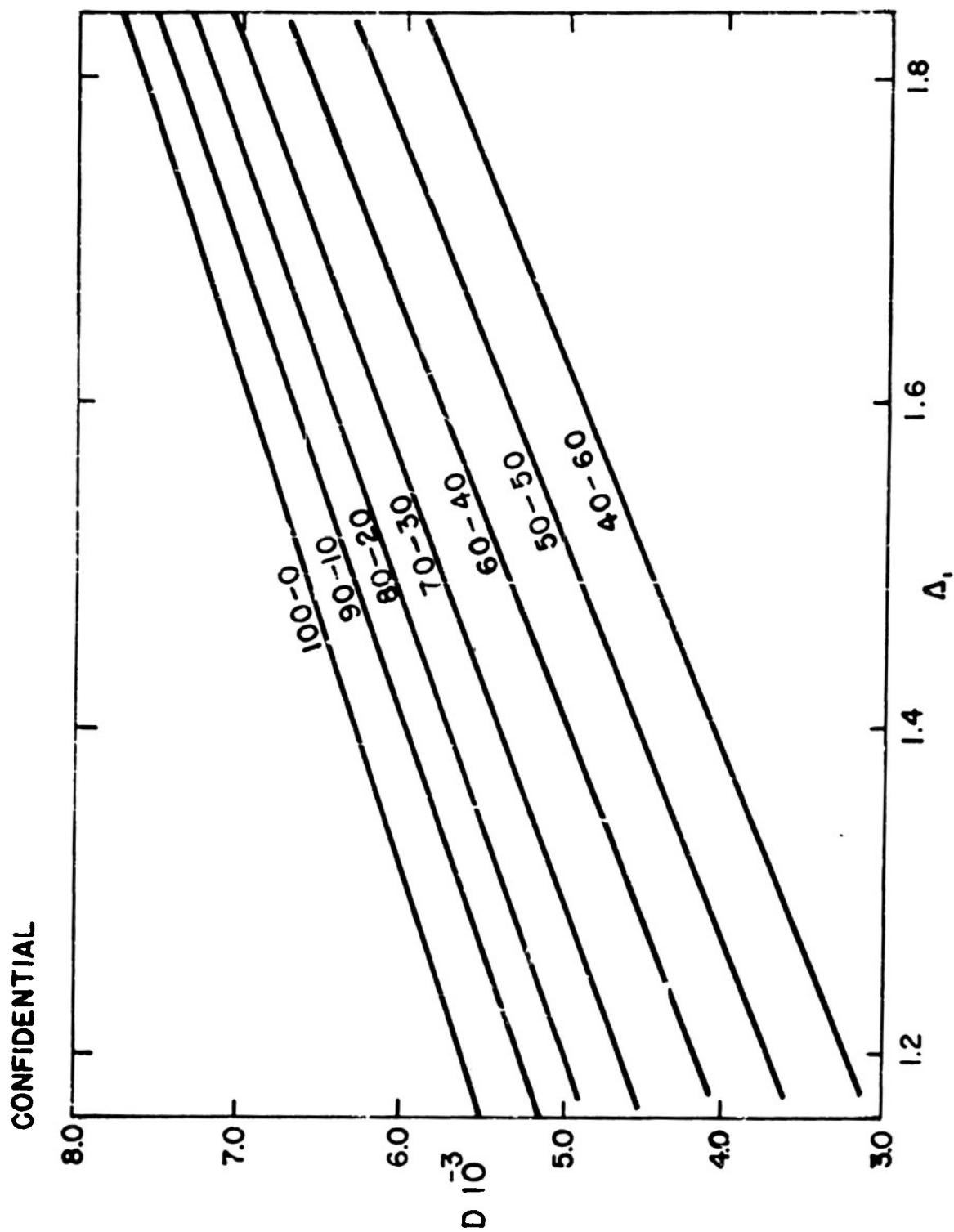


FIG.9 PREDICTED D VS Δ , DATA FOR TNT-SALT MIXTURE

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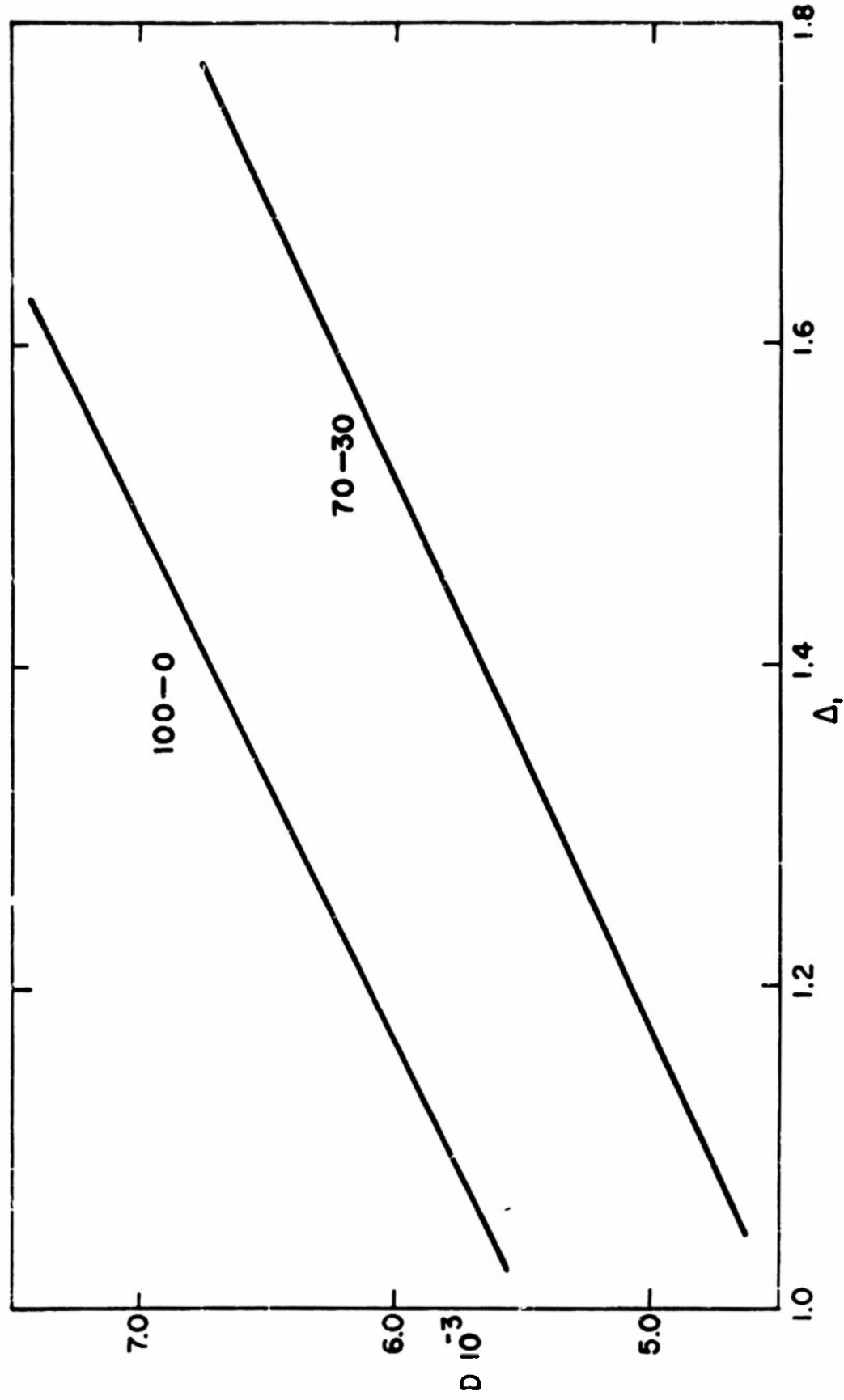


FIG.10 PREDICTED D VS Δ , DATA FOR 50-50 PENTOLITE - SALT MIXTURE

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